# CONTINUOUS RESISTANCE HEATING TECHNOLOGY – RISKS AND OPPORTUNITIES OF A NOVEL HEATING METHOD

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**Abstract:** *CoRe HeaT, the Continuous Resistance Heating Technology, is a novel heating method that can be used for carbon fibre placement processes such as the Automated Fibre Placement method, tape winding or alike. The paper gives a short overview of the technology and its main properties. The main disadvantage and risk of the technology is that it is not compatible with all common production materials. Only suitable carbon fibre materials can be heated using CoRe HeaT. While dry fibre tape material seems to be unproblematic, some prepreg tapes were found to be critical. Microscopic analysis and electrical resistance measurements seem to be an easy and fast method to determine whether a tape is suitable for continuous resistance heating or not. Aside from this risk, the technology offers the opportunity to increase productivity while reducing costs through high-speed heating and superior energy efficiency.*

**Keywords:** Automated Fibre Placement (AFP); Joule/ohmic/resistive/intrinsic heating; Carbon fibre reinforced plastic (cfrp); Manufacturing process

## 1. Introduction

Automated Fibre Placement (AFP) is one of the most common manufacturing processes for series production of carbon fibre reinforced plastic parts (cfrp) [1]. An important aspect for those processes is the heating technology. The increasing interest for thermoplastic part production and dry fibre process routes has pushed the development of new and improved heating technologies. The VCSEL laser [2], the Xenon Flashlamp [3] or use of ultrasonic heating [4] for example, have all been developed and tested for the AFP process within the last 5-10 years. Furthermore, the laser, as state of the art technology, has made a lot of progress [5].

An alternative to these AFP heating methods that has been in development for the past years, is direct electrical resistance heating, based on heating the electrically conductive carbon fibres using the Joule effect [6-9]. While static Joule heating of carbon fibres is known and has already been used for different purposes over the years [10], the focus of the Continuous Resistance Heating Technology (CoRe HeaT) is the AFP process and therefore heating unidirectional (UD) tapes or tows that are in movement. The electrical current is induced into the fibres via direct surface contact. Figure 1 shows how an AFP end effector heating zone configuration could be set up. In this example, the first electrical contact is in front of the consolidation roller. The second contact is the tooling. However, different electrode setups are possible with their own specific pros and cons. Within one of the electrical contacts, a current is induced. While flowing through the carbon tapes to the next electrical contact, the current produces heat within the fibres via the Joule effect.

  doi:10.5075/epfl-298799_978-2-9701614-0-0  

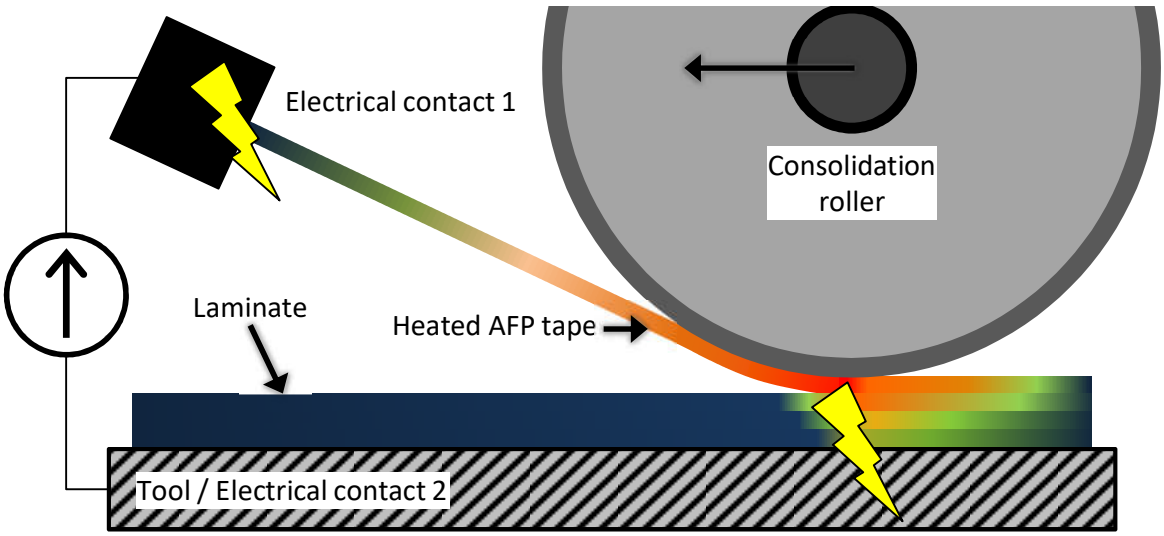


*Figure 1. Basic principle of a possible CoRe HeaT setup for the AFP process*

The resistive properties of carbon fibres are well suited for intrinsic ohmic heating. Theoretically heating rates much higher than other state of the art technologies are possible, even when limiting the applied electric voltages to the extra low voltage level (ELV), to prevent the dangers of an electric shock for humans [11]. ELV allows working directly next to the layup process without any special safety measures like laser proof housing or alike. Furthermore, in comparison to other high-speed heating technologies, the technology is cheaper, very compact and potentially easy to be integrated into an AFP end effector. In addition, directly heating the material with the Joule effect is highly energy efficient. Biggest drawback however is the limited compatibility of the technology to tape materials with suitable electrical properties.

## 2. Analysis of the pros and cons of CoRe HeaT

Focus of the current research is using the CoRe technology within the AFP process. It is one of the most common automated manufacturing processes and allows an automated test sample production. Furthermore, there is a wide variety of available research and literature focused on AFP [1]. Nevertheless, the findings and knowledge gained can also be used for all other manufacturing methods and technologies were carbon fibre materials need to be heated during dynamic transport. However, due to the need for direct electrical contact to the carbon fibres, not all materials that are common, are suitable for using CoRe HeaT. Next to the requirement of mainly being composed out of electrically conductive carbon fibres, the fibre distribution and especially the surface texture and composition play a major role. As long as raw and untreated carbon fibres are used, a general compatibility should be given. However, often the carbon fibres have been processed or modified, so that they are suitable for a chosen manufacturing method. With a focus on the AFP process, appropriate tape types were investigated.

### 2.1 Investigating material compatibility

Three main material types are common for the AFP process. The most common type is still the thermoset prepreg, available as tape or tow. However, this type of material needs only low process temperatures, typically below 70°C [1], reducing the need for high-intensity heating technologies. Also, the sticky thermoset matrix system covering the fibres is a potential problem for direct electrical surface contacts due to contamination. Furthermore, alternate process

routes that use dry fibre tape material with a separate matrix infusion or injection offer a lot of advantages. First aircraft wings are already being manufactured in this way [12] and several research projects have focused on dry fiber placement [13].

Dry fibre tapes are fundamentally different to pepreg tapes. They are usually composed out of spread raw carbon fibre rovings that are stabilized with the help of auxiliary materials like non-woven veils, hotmelt powder binders or a combination of those or similar products. Their process temperatures go up to 200°C and above, making faster heating technologies beneficial. The auxiliary veils and binders are normally electrically isolating. However, their weight-based percentage is normally below 10 %. Figure 2 shows microscopic images of the surfaces of different dry fibre materials. The two pictures on the left show the bindered surfaces of different AFP tape materials where large areas of raw carbon fibres are still clearly visible. These tapes were well suited for the CoRe heating technology due to good contact properties. The surface in the right picture is covered with an electrically isolating veil. Even though the carbon fibres are also still visible in the background, the veil surface of this tape was not well suited for the process, since the three-dimensional structure of the veil in combination with its stiffness, made it nearly impossible to get a good contact to the fibres. However, the other side of the tape did not have a veil, had good contact properties and therefore could still be used. For dry fibre tapes, without an isolating matrix within, it is sufficient if at least one side of the tape has good electrical contact properties. So far, all tested dry fibre tapes and tows composed of high strength (HS), high tenacity (HT) or intermediate modulus (IM) carbon fibres in combination with epoxy or thermoplastic based veil or powder binders of several different suppliers were well suited for using CoRe HeaT.

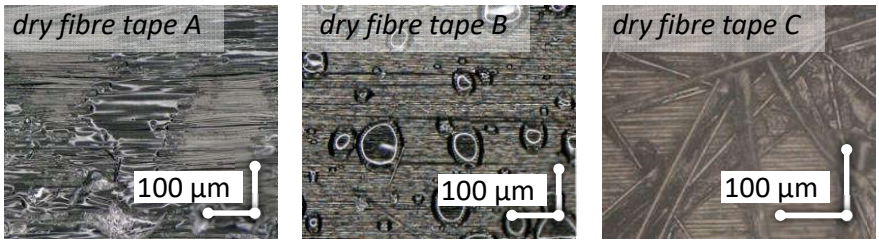


*Figure 2. Microscopic look at the surface of different dry fibre tows and their composition*

Thermoplastic prepreg tapes are the third type of tapes that are in focus. They have received increasing attention in recent years, due to their advantages in regard to increased toughness, better recyclability and especially faster manufacturing and assembling because of their welding capabilities [14]. With process temperatures of up to 400°C and above, they are the most demanding material type. An important aspect of these tapes in regard to CoRe HeaT is that the fibres are already pre-impregnated with the matrix system. The electrically isolating properties of the matrix can be a problem. For a good compatibility to direct electrical heating, the tapes need a high fibre volume content, a homogeneous fibre distribution within the tape and enough uninsulated fibres on the surface of the material. Figure 3 shows the micrographs of two different tapes, with the left one having much better properties in regard to Joule heating than the right one. Since the electrical current always seeks the path of least resistance, a fiber distribution that is as uneven as in the picture on the right, can lead to an equally uneven temperature distribution.

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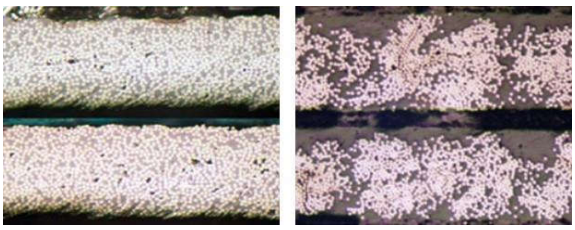

*Figure 3. Two different thermoplastic prepreg tapes and their fibre distribution* [15]

The requirement of a good electrical contact resistance of the surface of the tape is even more important for an even temperature distribution without hotspots. Available thermoplastic prepreg tapes differ a lot in this regard. A first visual inspection can help to determine whether the tape is potentially compatible or not. Smooth flat shiny tapes indicate a resin-rich surface with a high electrical resistance and only a few contact zones, leading to severe hotspots. A matt looking surface where the fibres can be seen, could indicate a potential compatibility. However, a closer look is needed to understand why some prepreg tapes can be used for continuous high speed direct electrical resistance heating and others are not. Figure 4 shows a microscopic image of the surface of different prepreg tapes. The investigated tapes belong to the group of polyaryletherketones (PAEK), except for tape D, which is a polyamide 6 (PA6) prepreg. The right picture shows the PA6 tape, with a smooth and shiny surface that is nearly completely covered by resin and is therefore unsuitable. The left picture shows the matt surface of a PAEK tape, where the fibre structure can be seen. Nevertheless, a very close look with a magnification of 2000x shows that there is a thin shiny thermoplastic film covering most of the fibres completely. Layup trials using this tape revealed the problematic consequences of such a surface condition, which were uneven temperature distributions during layup. Especially at higher layup speeds from 0.5 m/s and above, severe hot spots with clearly visible damage to the material surface occurred. The second picture on the right shows a microscopic look on the surface of another PAEK prepreg tape, that seemed well suited for the process. In contrast to *prepreg tape A* on the left, it can be seen that the fibers on the surface are not completely covered by resin. The rough structured look of the raw carbon fibers can be clearly distinguished from areas where they are covered with resin. This tape was tested with a layup speed of up to 1 m/s with seemingly good results.

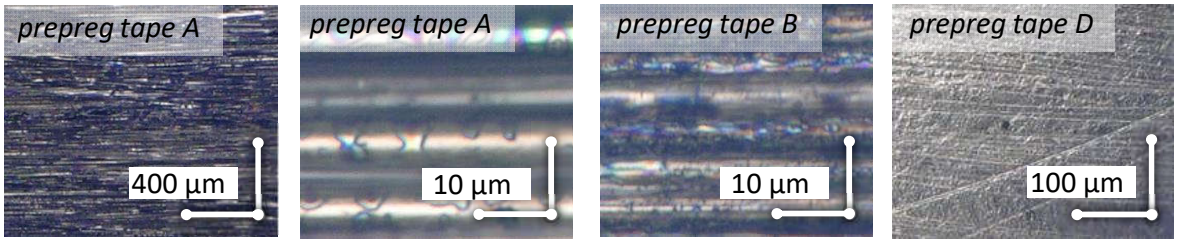


*Figure 4. Different thermoplastic prepregs and their surfaces in detail*

The optical inspection however is just a way to further understand why certain tapes are more suitable than others. A practical attempt to determine the compatibility is by testing the materials electrical properties in detail. An important factor that is expected to correlate with the compatibility to continuous resistance heating, is the surface contact resistance. Therefore, the electrical properties of different tape materials were tested, to get an indicator on how well they are suited for CoRe HeaT.

  

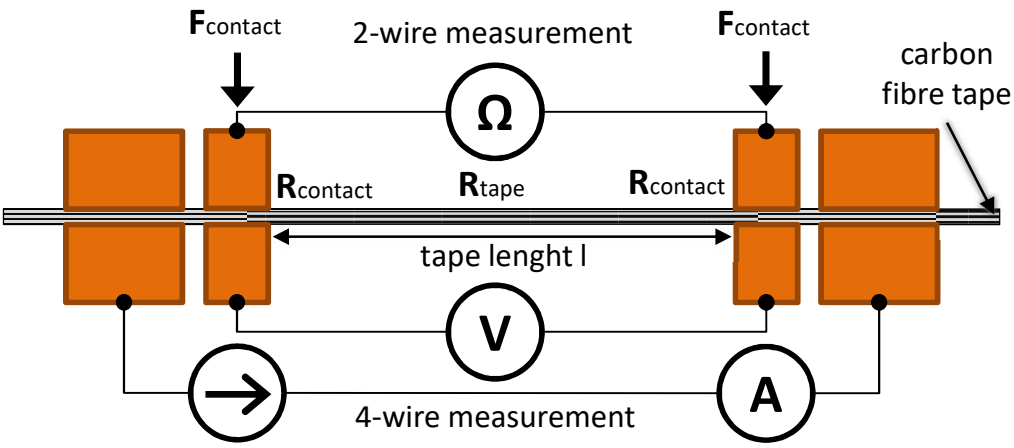


*Figure 5. Sketch of the resistance test setup*

The test setup used to determine the contact resistance can be seen in figure 5. It is a 4-wire resistance measurement setup with pneumatically actuated contacts, so that the contact forces can be varied, in combination with a standard 2-wire test circuit.

The 4-wire measurement gives an exact reading of the tape's resistance ($R_{tape}$) without the contact resistances ($R_{contact}$). The 2-wire setup measures the total resistance ($R_{total}$), including these. Therefore, the contact resistance can be determined by subtracting the value of the 4-wire resistance measurement ($R_{4w}$) of the 2-wire resistance value ($R_{2w}$).

$$R_{contact} = R_{total} - R_{tape} = R_{2w} - R_{4w} \quad (1)$$

Table 1 shows the average contact resistances with a low contact force ($R_{c-lcF}$), a high contact force ($R_{c-hcF}$) and the maximum difference between the lowest and the highest measured contact resistances (Δmax) in a series of 5 measurements. The investigated tapes *A*, *B* and *D*, are the same that have been discussed in the microscopic analysis above. *Prepreg tape C* is another newly introduced PAEK tape, which is a thin-ply prepreg with an aerial weight of only 40 g/m². The *bindered dry fibre tape A*, from figure 2, is listed as a reference. It has already been thoroughly tested and seems to be very well suited for the CoRe heating technology. Layup speeds with up to 2 m/s were unproblematic and an inter laminar shear strength (ILSS) test series showed no negative influences of high intensity resistance heating on the specimen [7]. The *thermoplastic prepreg tape A* has been tested with layup speeds of up to 0.25 m/s with an acceptable result in regard to temperature homogeneity and optical inspection of the layup quality. At higher speeds however, hot spot severity increased to a point that was unacceptable. P*repreg tape B* is the tape that has been tested with a layup speed of 1 m/s without any problems. The thin-ply *prepreg tape C* was already successfully tested with a maximum layup speed of 2 m/s, also without any noticeable problems. *Thermoplastic prepreg tape D* has not yet been tested with the AFP prototype. Even though the average contact resistance is lower than *prepreg tape A*, it is expected that *prepreg tape D* will perform worse, due to a much higher scattering of the contact resistances (Δmax). The experience made so far, supports the theory that high contact resistance with high scatter corresponds to poor compatibility with the CoRe heating technology.

*Table 1: Different tape materials and their electric properties*

| Material type | $R_{c-lcF}$ [Ω] | $R_{c-hcF}$ [Ω] | Δmax [Ω] |
|---|---|---|---|
| Bindered dry fibre tow A | 2,6 | 0,6 | 3,6 |
| Thermoplastic prepreg tape A | 43,1 | 13,3 | 60,3 |
| Thermoplastic prepreg tape B | 3,7 | 2,0 | 5,7 |
| Thermoplastic prepreg tape C | 4,0 | 0,3 | 5,0 |
| Thermoplastic prepreg tape D | 31,5 | 7,4 | 115,0 |

### 2.2 Highly dynamic heating

One of the reasons why CoRe HeaT could be interesting to use in a process, is the highly dynamic heating capability. Extreme process acceleration and process speeds faster than current state of the art technologies, allow an increase in productivity. The maximum estimated speed for different types of materials, that are listed in table 2, are mainly limited by the extra low voltage limitations [11]. In theory, specialized machines were human interaction during processing is not needed, raising the electric process voltage would allow even higher process speeds. Another technology related aspect that has an influence on the maximum process speed when a voltage limit is given, is the heating zone length and design details regarding the heating unit [16]. Besides technical related influences, the tape material properties are an important factor. As described before, critical temperature distribution due to bad compatibility might limit the maximum layup speed. Furthermore, the required process temperature, the tapes specific weight, its specific heat capacity and the electrical properties all have an influence on the maximum process speed. Table 2 is therefore only intended to give an idea of the potential maximum layup speeds, with this estimation being constrained by a maximum process voltage that remains within the ELV limit.

*Table 2: Maximum estimated layup speeds in regard to materials contact resistances, the area specific weight, the layup temperature and tested layup speeds*

| Material type | Materials $R_{c-hcF}$ [Ω] | Materials weight [g/m²] | Layup temperature [°C] | Max speed tested [m/s] | Max speed estimated [m/s] |
|---|---|---|---|---|---|
| Dry fibre tow A | 0,6 | 210 | 160 | 2,0 | > 32 |
| Prepreg tape A | 13,3 | 145 | > 380*² | 1,0 | < 0,5* |
| Prepreg tape B | 2,0 | 194 | > 340*² | 1,0 | 2,7 |
| Prepreg tape C | 0,3 | 40 | > 340*² | 2,0 | >7,0 |

* Higher layup speeds led to severe hot spots and heat damages to the tape material.
*² Estimated layup temperatures based on materials melting point or measured temperatures ahead of nip point (maximum) temperature.

  

### 2.3 Green low-cost technology

Since the technology is not yet commercially available, it is not possible to compare exact prices. However, based on hardware costs of the prototype and known costs for comparable laser or flashlamp systems, it is expected that the price for a CoRe heating unit will be significantly lower, by at least 30 %. In comparison to laser systems, another big cost reduction factor is that no laser proof housing is needed. Especially for larger production facilities, laser proof housing could easily cost 100.000 € or even much more, depending on the machines size. Another aspect making CoRe HeaT a green low-cost technology is the superior energy efficiency. Using the Joule effect, the electrical energy flowing through the fibres is directly transformed into heat without energy losses [17]. As with the maximum process speed, the material properties, the design of the heating unit and the selected process parameters have an influence on the final energy efficiency. Table 3 is listing the used power for different layup trials using CoRe HeaT and data found in publications regarding the use of a laser or a flashlamp heating system, to get a rough comparison of energy usage. Since the materials weight, the layup speed and especially the process temperature generally have a significant impact on the energy efficiency, the final results listed for power consumption in watts per tape and process speed should only be understood as a very rough estimate. Furthermore, the information found in publications are often not detailed enough or instead of the electrical power usage of a laser, the optical power is given.

*Table 3: Energy consumption for different materials and process parameters in comparison to different heating technologies*

| Material type | Materials weight [g/m²] | Layup speed [m/s] | Layup temperature [°C] | Heating technology | Power usage [W/tape] | Power usage [W/tape·m/s] |
|---|---|---|---|---|---|---|
| Bindered dry fibre tape A | 210 | 0,75 | 160 | CoRe HeaT | 150 | 200 |
| Thermoplastic prepreg tape B | 194 | 1,0 | > 340* | CoRe HeaT | 1500 | 1500 |
| Thermoplastic prepreg tape A | 145 | 0,15 | > 380* | CoRe HeaT | 320 | 2133 |
| Thermoplastic prepreg tape A | 194 | 0,11 | 365 | Flashlamp | 975*² | 8864 |
| Cytec APC-2 C/PEEK | <200*³ | 0,2 | 450 | Laser | 1000 | 5000 |

* Estimated values based on materials melting point or measured temperatures ahead of nip point (maximum) temperature.
*² Multitow Layup unit, therefore total power divided by tows that were processed [18]
*³ No information on aerial weight, but with a mentioned thickness of 0.135 mm per ply, the estimated aerial weight is lower than 200 g/m² [19]

## 3. Summary and conclusion

A critical aspect of the CoRe Heating technology is that it only works with carbon fibre materials, that have a surface where the fibres themselves are easily contactable. Therefore, the main question whether this novel heating method could be usable with a certain process in mind, must be answered by looking at the desired process materials first. The main requirement of being mainly composed out of carbon fibres is just the start. With a focus on AFP carbon fibre tapes, two different ways how to analyze the materials and estimate their compatibility are presented. A close up look with a microscope and a 2000x magnification allows to see whether individual fibres are lying open or if they are covered by an electrical isolator. However, other aspects of the materials properties might hinder direct electrical contact. For example, the stiffness of surface covering electrically isolating veils, which could not directly be determined via a microscope. Another method that seems to give good values for compatibility evaluation is resistance measurement. The results of a test setup were the resistance between contact electrodes and the carbon fibre material could be determined, seems to have a good correlation to practical process experiences in regard to material compatibility.

Nevertheless, further research is needed to determine whether a material is fully compatible and therefore without any risks regarding part manufacturing, since high process speeds might become a problem for some materials.

The low costs of the technology and the extremely high potential process speeds however, make this an interesting new alternative for future carbon fibre processing machines.

## Acknowledgements

The Author would like to thank the German Federal Ministry of Education and Research (BMBF) for supporting the research by funding the project ThermoPros (03INT713BG).

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